INFRARED SPECTROSCOPIC DIAGNOSTICS FOR ACTIVE GALACTIC NUCLEI

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Abstract. Infrared spectroscopy in the mid- and far-infrared provides powerful diagnostics for studying the emission regions in active galaxies. The large variety of ionic fine structure lines can probe gas conditions in a variety of physical conditions, from highly ionized gas excited by photons originated by black hole accretion to gas photoionized by young stellar systems. The critical density and the ionization potential of these transitions allow to fully cover the density-ionization parameter space. Some examples of line ratios diagrams using both mid-infrared and far-infrared ionic fine structure lines are presented. The upcoming space observatory *Herschel* will be able to observe the far-infrared spectra of large samples of local active galaxies. Based on the observed near-to-far infrared emission line spectrum of the template galaxy NGC1068, are presented the predictions for the line fluxes expected for galaxies at high redshift. To observe spectroscopically large samples of distant galaxies, we will have to wait fot the future space missions, like SPICA and, ultimately, FIRI.

1 Introduction

The spectroscopic observations of the *Infrared Space Observatory* (ISO) (Kessler et al. 1996) opened a new window for the study of the physical and chemical properties of IR-bright, ultraluminous infrared galaxies (ULIRG) and active galactic nuclei (AGN). Most of the pioneering work on the mid-to-far infrared spectra of active and starburst galaxies is derived from ISO spectroscopy (Sturm *et al.* 2002; Spinoglio *et al.* 2005; Verma *et al.* 2003; Verma *et al.* 2005).

The mid-IR spectral range includes most of the fine-structure lines excited by the hard radiation produced by black hole accretion as well as those mainly excited by stellar ionization (Spinoglio & Malkan 1992) and thus represents an essential tool to distinguish between the two processes, especially in obscured nuclei

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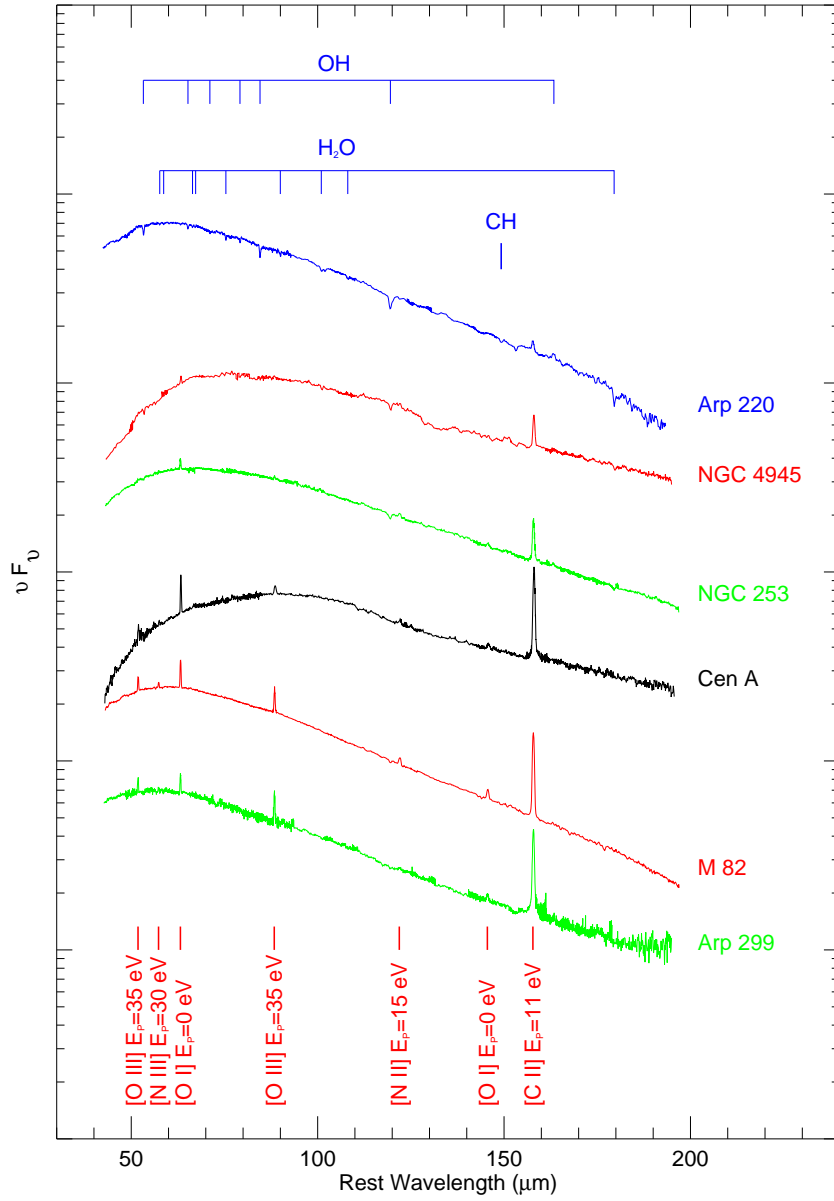
Fig. 1. Far infrared spectra observed with the LWS onboard of ISO of a sample of ultraluminous infrared galaxies (Fischer *et al.* 1999)

suffering severe dust extinction. With the advent of the *Spitzer Space Telescope*, with its powerful mid infrared instrument, the IRS (Houck *et al.* 2004), systematic spectroscopic studies of samples of galaxies have stated to appear (Dale *et al.* 2006;

Higdon *et al.* 2006; Brandl *et al.* 2006; Armus *et al.* 2007; Farrah *et al.* 2007; Buchanan *et al.* 2006; Tommasin *et al.* 2007).

In a complementary way, the far-IR range contains a large variety of molecular (OH, H_2O, high-J CO) and low excitation ionic/atomic transitions, in emission or in absorption, that can reveal the geometry and morphology of the circumnuclear and nuclear regions in galaxies. In particular far-infrared molecular lines could trace the expected conditions of X-UV illuminated dusty tori predicted from the unified models (Antonucci 1993 and whose presence in type 2 active galaxies is foreseen to reconcile the type1/type2 dichotomy.

The far-IR spectra of local IR-bright and ULIRG galaxies, as measured by ISO-LWS (Fischer *et al.* 1999), showed an unexpected sequence of features, as can be seen in Fig. 1, from strong [OIII]52, 88 μm and [NIII]57 μm line emission to detection of only faint [CII]157μm line emission and [OI]63 μm in absorption. The [CII]157 μm line in 15 ULIRGs ($L_{IR} \geq 10^{12} L_\odot$) revealed an order of magnitude deficit compared to normal and starburst galaxies relative to the FIR continuum. Non-PDR components, such as dust-bounded photoionization regions, generating much of the FIR continuum but not contributing significant [CII] emission, can explain the [CII] deficiency. Such environments may also explain the suppression of FIR fine-structure emission from ionized gas and PAHs, and the warmer FIR colors of ULIRGs. (Luhman *et al.* 2003).

LWS observations of Arp 220 show absorption in molecular lines of OH, H_2O, CH, NH, and NH_3, as well as in the [OI]63μm line and faint emission in the [CII]158μm line. The molecular absorption in the nuclear region is characterized by high excitation due to high infrared radiation density (González-Alfonso *et al.* 2004). Notably, the LWS spectrum of the prototype Seyfert 2 galaxy NGC 1068, beside the expected ionic fine structure emission lines, shows the 79, 119 and 163μm OH rotational lines in emission, not in absorption as in every other galaxy yet observed. Modeling the three FIR lines of OH suggests the gas lies in small (0.1pc) and dense clouds ($\sim 10^4 cm^{-3}$) in the nuclear region (potentially a signature of the torus) with a minor contribution from the circumnuclear starburst ring at 3kpc (Spinoglio *et al.* 2005).

2 Fine-structure emission lines

Mid-IR and far-IR spectroscopy of fine-structure emission lines are powerful tools to understand the physical conditions in galaxies from the local universe to distant cosmological objects. Fig. 2 shows the critical density (i.e. the density for which the rates of collisional and radiative de-excitation are equal) of each line as a function of the ionization potential of its ionic species. This diagram shows how these lines can measure two fundamental physical quantities (density and ionization) of the gas. Lines from different astrophysical emission regions in galaxies are shown in the figure with different symbols. The ratio of two lines with similar critical density, but different ionization potential, gives a good estimate of the ionization, while the ratio of lines with similar ionization potential, but with diffrerent critical density, can measure the density of the gas in the region (see, e.g., Spinoglio &
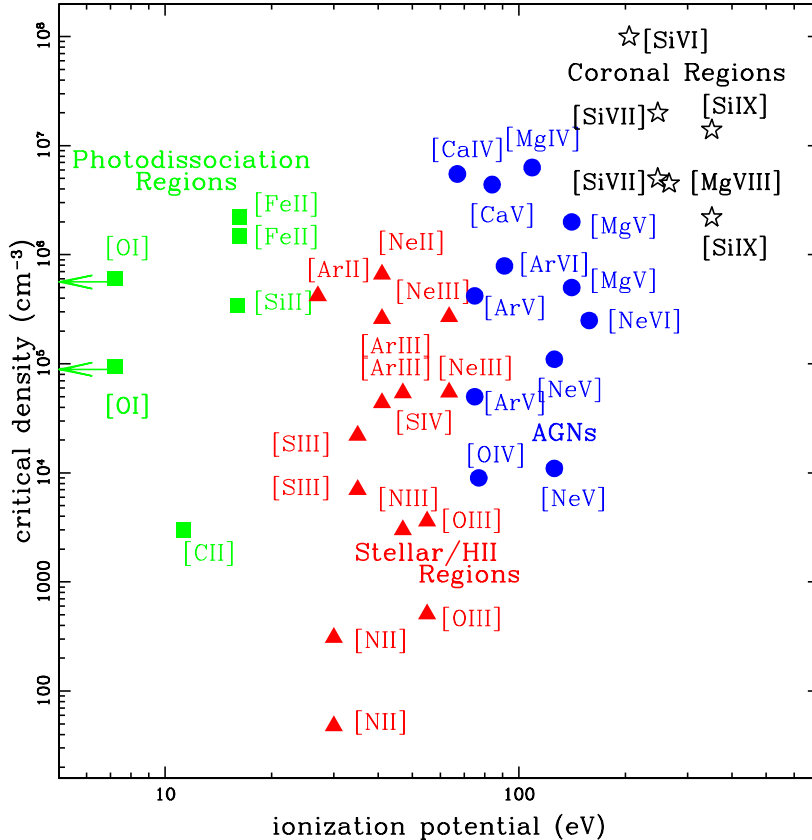
Fig. 2. Fine-structure lines in the 3-200 μm range. The lines are plotted as a function of their ionization potential and critical density. Different symbols are used for lines from photodissociation regions (squares), stellar/HII region lines (triangles), AGN lines (circles) and coronal lines (stars). The two [OI] lines have been plotted - for graphical reasons - at a ionization potential higher than their effective value.

Malkan 1992). From Fig. 2 it is clear that infrared spectroscopy has a thorough diagnostic power for gas with densities from about 10^2 cm^{-3} to as high as 10^8 cm^{-3} and ionization potentials up to 350 eV, using, to trace these extreme conditions, the so called coronal lines. Moreover, increasing the wavelength of the transition used, the spectroscopic diagnostics become more and more insensitive to dust extinction, and can therefore probe regions highly obscured at optical or even near-to-mid infrared wavelengths.

To give an example of the diagnostic power of infrared spectroscopy, we show in Fig. 3 a diagram showing lines excited only in the highly energetic environments of
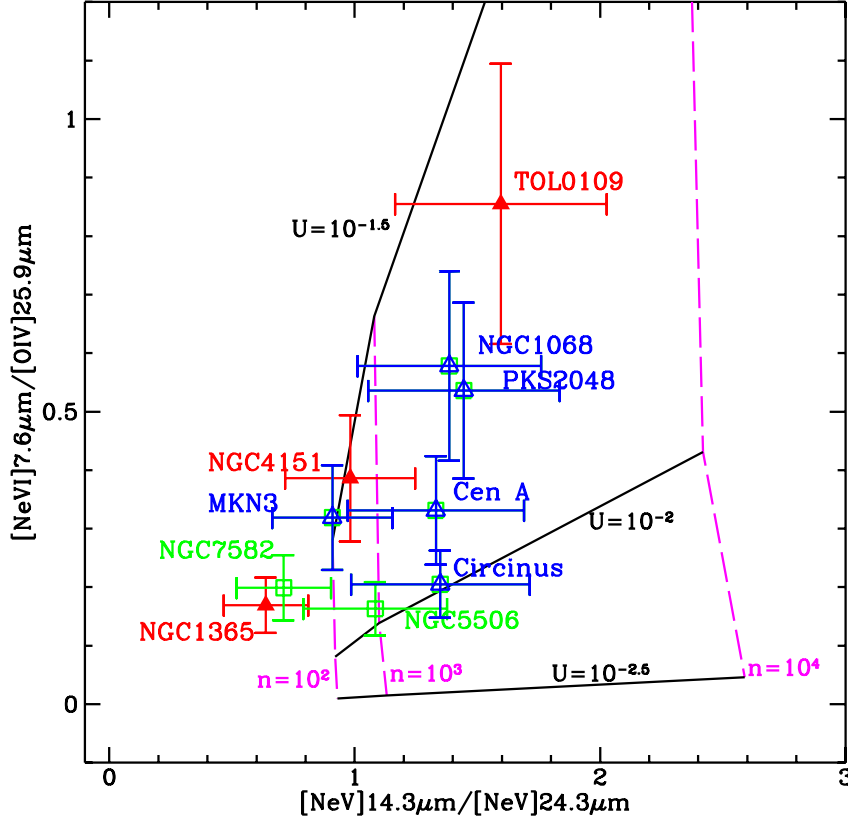
Fig. 3. [NeVI]7.6μm/[OIV]26μm ratio as a function of the [NeV]14.3μm/24.3μm ratio. The line rations of Seyfert 1's (NGC1365, NGC4151, Tol0109), Seyfert 2's (MKN3, CenA, Circinus, NGC1068, PKS2048) and NLXR galaxies (NGC5503, NGC7582) are presented, from ISO SWS observations (Spinoglio *et al.* 2000; Sturm *et al.* 2002).

AGN and not from stellar ionization. In this diagram the [NeVI]7.6μm/[OIV]26μm ratio is shown as a function of the [NeV]14.3μm/24.3μm ratio (Spinoglio *et al.* 2000). The photoionization models using the CLOUDY code (Ferland 2000) have been computed and shown as a grid in the diagram. As expected, the former ratio is sensitive to ionization, while the latter is sensitive to density. In the figure are also shown measurements on a small sample of Seyfert galaxies for which we can determine the ionization potential (basically the ratio of ionizing photons over the number of hydrogen atoms) and the gas density. We note that the observed galaxies have average densities ranging from less than 10^2 cm^{-3} to less than 10^4 cm^{-3} and ionization potential of $10^{-2.0} < \log U < 10^{-1.5}$. This is in agreement, for
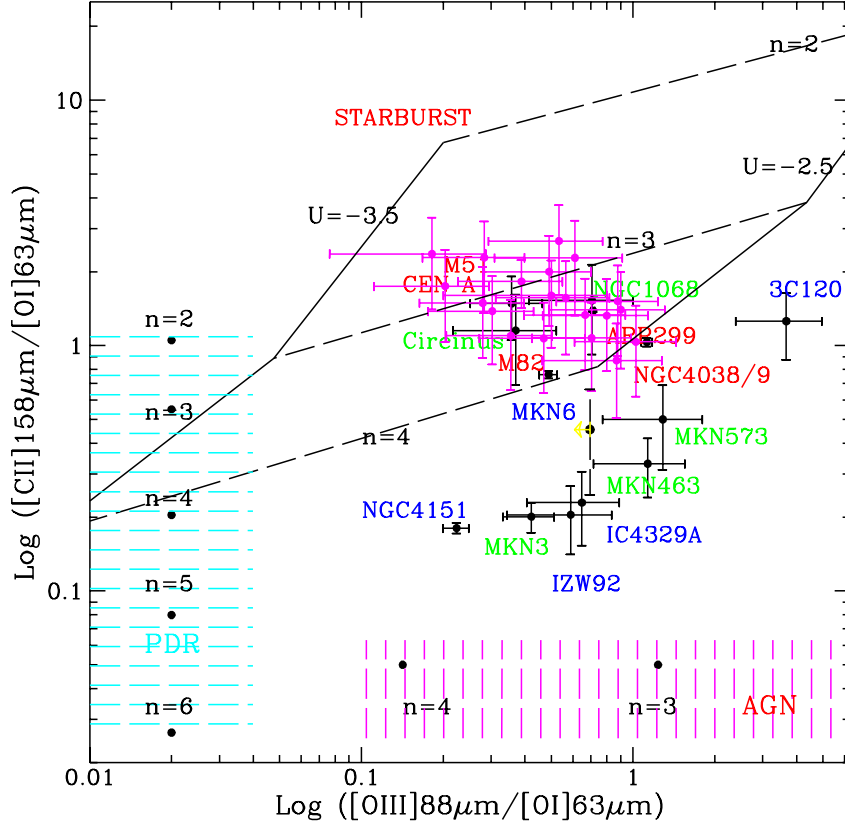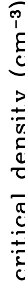
Fig. 4. [CII]157μm/[OI]63μm ratio as a function of the [OIII]88μm/[OI]63μm ratio. The grid represents starburst photoionization models computed using the CLOUDY code. At the right bottom are shown the gas density values as derived from AGN photoionization models with log U = -2.5, while at the left are given the densities derived from photodissociation region models (Spinoglio *et al.* 2003).

the lower density objects, with conditions of "coronal emission regions" in AGNs (Spinoglio & Malkan 1992).

Another example, presented in Fig. 4, is given by the [CII]157μm/[OI]63μm ratio as a function of the [OIII]88μm/[OI]63μm ratio. These low ionization lines are copiously produced in the ISM of galaxies (in photodissociation regions) and the [OIII] line is excited also in HII regions. However we can see from this diagram that while normal galaxies are clustering in a central region that can easily be explained by starburst models, most of the Seyfert galaxies are far from this locus and their rations cannot be reproduced by starburst models. They have much

Fig. 5. Same as fig.1, but for differerent redshift intervals. Different symbols are used for lines from photodissociation regions (squares), stellar/HII region lines (triangles), AGN lines (circles) and coronal lines (stars). The two [OI] lines have been plotted - for graphical reasons - at a ionization potential higher than their effective value.

stronger emission of [OI]63μm than it would be expected from stellar emission only. To obtain better statistics on this diagram, we will have to wait for the *Herschel* satellite, that will have the sensitivity to collect far-infrared spectroscopic observations of large samples of local galaxies.

3   From the local to the distant Universe

Mid-IR and far-IR spectroscopy of fine-structure emission lines can be used not only in the local universe but also to measure the excitation conditions in distant cosmological objects. Fig. 5 shows again, as in Fig.2, the critical density of the

lines as a function of their ionization potential, not only for the local universe, but in three different redshift ranges, one for each frame, for which the rest-frame wavelength of the line is shifted in the far-infrared range. It appears from the figure that although the photodissociation (PDR) regime can be probed only in the relatively local universe, because of the long wavelengths of the lines tracing this regime, however, the stellar emission (e.g. in starburst galaxies) can be probed up to high z, using many lines in the rest-frame spectral range of $3 \leq \lambda(\mu m) \leq 30$. Moreover, the ionization from AGN can be probed from the local universe up to redshifs of z$\leq$5 and the extremely high excitation coronal emission regions are probed by near-IR lines shifted into the far-IR at a redshift of z $\sim$ 5.

Once we have proved that we have in the mid-to-far infrared the adequate diagnostic lines, we need still to understand if these lines could be detected by the future space facilities under development or study in the future years. Do do so, we will use the observed infrared spectra in local galaxies and let them evolve backwards at earlier cosmological times.

For simplicity, and to cover as many transitions possible, we use a local object which contains both an active nucleus and a starburst, the bright prototype Seyfert 2 galaxy NGC1068. The ISO spectrometers detected in this galaxy many of the lines plotted in Fig. 2 at flux levels of 5-200 $\times$ 10^{-16} W m^{-2} (Alexander *et al.* 2000; Spinoglio et al. *et al.* 2005). Considering this galaxy as a template object, we computed the line intensities expected at redshifts ranging from 0.1 to 5. For simplicity, we adopted an Einstein-De Sitter model Universe, with $\Omega_\Lambda = \Omega_{vac} = 0$ and Ω_M= 1, H$_0$=75 km s^{-1} Mpc^{-1}. The luminosity distances have been derived using:

$$d_L(z) = (2c/H_0) \cdot [1 + z - (1 + z)^{1/2}] \tag{3.1}$$

The results are reported in Fig. 6, where the line intensities are given in W m^{-2}, and the expected sensitivities of spectrometers, such ESI (European SPICA Instrument, Swinyard 2006), onboard of the future space observatories, SPICA (Space Infrared Telescope for Cosmology and Astrophysics, ISAS-JAXA) (Nakagawa 2004; Onaka & Nakagawa 2005) and FIRI (Far-Infrared Interferometer) are also shown.

We have assumed that the line luminosities scale as the bolometric luminosity and we have chosen two cases:
A) a luminosity evolution proportional to the (z+1)^2, consistent with the *Spitzer* results at least up to redshift z=2 (Pérez-González *et al.* 2005) ;
B) no luminosity evolution.

Because the star formation process in galaxies was much more enhanced at z=1-2 than today, we consider reasonable to adopt the model with strong evolution at least for the stellar/HII region lines and, to be conservative, the "no evolution" one for the AGN lines.
We note that the dependence on different cosmological models is not very strong. The popular model with Ω_M= 0.27, Ω_{vac}=0.73, H$_0$=71 km s^{-1} Mpc^{-1} shows greater dilutions, increasing with z, by factors of 1.5 for z=0.5 to 2.5 for z=5. In
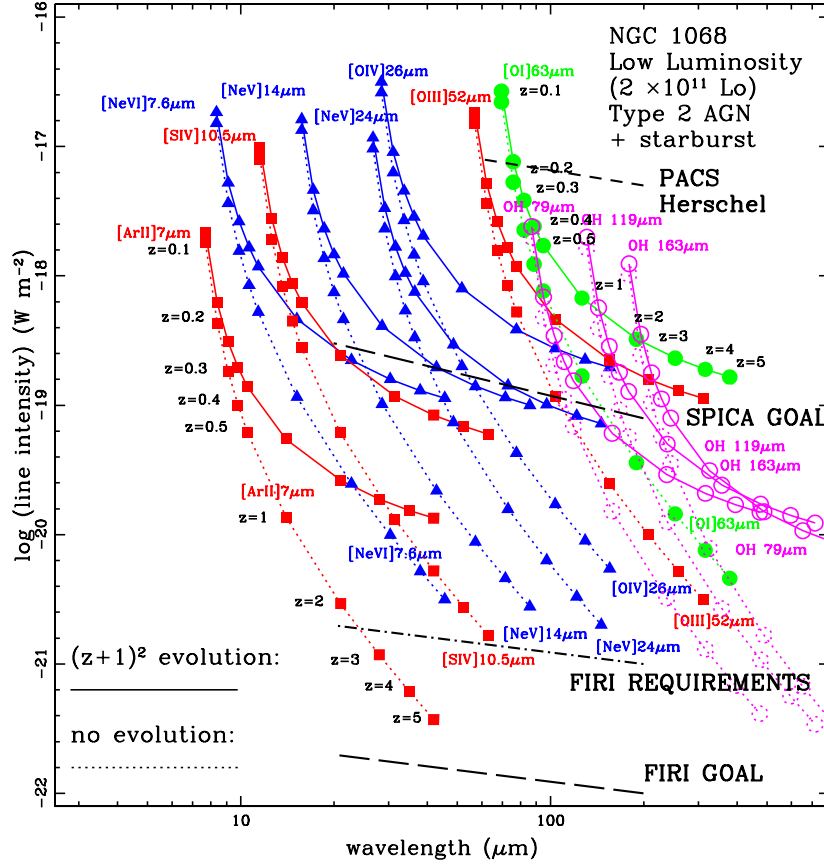
Fig. 6. Predicted line fluxes as a function of redshift, using as a local template the prototypical Seyfert type 2 galaxy NGC1068. Squares indicate the fluxes of HII region lines, triangles the fluxes of lines emitted by AGN, filled circles the fluxes of the [OI]μm line and open circles the three OH lines detected in emission in NGC1068. The solid lines show how the line fluxes change with redshift adopting luminosity evolution, while dotted lines without any evolution.

this case the line intensities of Fig. 6 would decrease by these factors.

We conclude that a relatively low luminosity object like NGC1068, with an infrared luminosity of 2×10^{11} L$_\odot$, will be detected up to a redshift of z=5 by the cooled 3.5m mirror of the SPICA satellite in a few bright and important diagnostic lines, such as the [OI]63μm, the [OIII]52μm, [OIV]26μm, assuming luminosity evolution in the lines.

The fainter AGN lines (like [NeVI]7.6μm) and the molecular lines of OH, will be detected by SPICA in such an object at z $\sim$ 0.5. For detecting the fainter lines

up to z $\sim$ 5, we will have to wait for larger collecting area space telescopes, as the FIRI project, foreseen beyond the next decade.

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